

Use of Nanotechnology in Food Industry: A review

Dibyaranjan Samal

Department of Biotechnology, AMIT College, Khurda 752057, Odisha, India

Abstract— Food science is emerging in a fast way with collaboration of nanotechnology. The food market demands technologies, which are essential to keep market leadership in the food processing industry to produce fresh authentic, convenient and flavorful food products and nanotechnology is the answer to it. Nano particles are used as nano inside as additives and nano outside as packaging. The packaged food products are proving more health beneficial and hygiene with the help of nanotechnology. Nano particles are using as food additives makes food to stay away from microbial contamination hence lengthening the lifespan. Nanoscale food additives may for example be used to influence product shelf life, texture, flavor, nutrient composition, or even detect food pathogens and provide functions as food quality indicators. Nanotechnology provides a vast range of opportunities for the development of new products and applications in food system. Functional foods, nutraceuticals, bioactives, pharmafoods, etc. are very recent example of it. Lowering of the cost of food additives is a milestone of using nano food additives.

Keywords— Nano Foods, Nano Emulsion, Nanoencapsulation.

I. INTRODUCTION

Nanotechnology is the field deals with the materials of nanoscale. The National Nanotechnology Initiative calls it “nanotechnology” if only, “the research and technology development at the atomic, molecular or macromolecular levels, in the length scale of approximately 1-100 nanometer range, creating and using structures, devices and systems that have novel properties and functions because of

their small and/or intermediate size and ability to control or manipulate on the atomic scale” [Ozimek et. al 2010]. Nano Particles are typically results in greater chemical activity, biological activity and catalytic behavior compared to large particles of the same composition. In food nano particles are used as additives such like preservatives, flavoring agent, antimicrobial sensors etc. and packaging substances. Nanotechnology provides a vast range of opportunities for the development of new products and applications in food system. Functional foods, nutraceuticals, bioactives, pharmafoods, etc. are very recent example of it. Nano particles of Titanium dioxide, Silver, Zinc, Zinc Oxide, Silicon dioxide, Platinum, Gold are use vastly in food industry in different forms [Alfadul&Elnehwya2010]. In human food processing, nanocapsules have been used as nano-sized ingredients, additives, nutritional supplements, and in functional foods reported that nanoencapsulation of food ingredients and additives have been carried out to provide protective barriers, flavor and taste masking, controlled release, and better dispensability for water-insoluble food ingredients and additives [Mahmoud 2015]. They are also aiming to develop improved tastes, reduce the amount of salt, sugar, fat and preservatives, address food-related illnesses (e.g. obesity and diabetes), develop targeted nutrition for different lifestyles and aging population, and maintain sustainability of food production, processing and food safety [Chaudhry et al. 2008]. Nanoparticles and Nano capsules containing several foods are currently available for purchase, though without being required to indicate the presence of these Nano-materials on their packaging [Paul&Dewangan 2016].

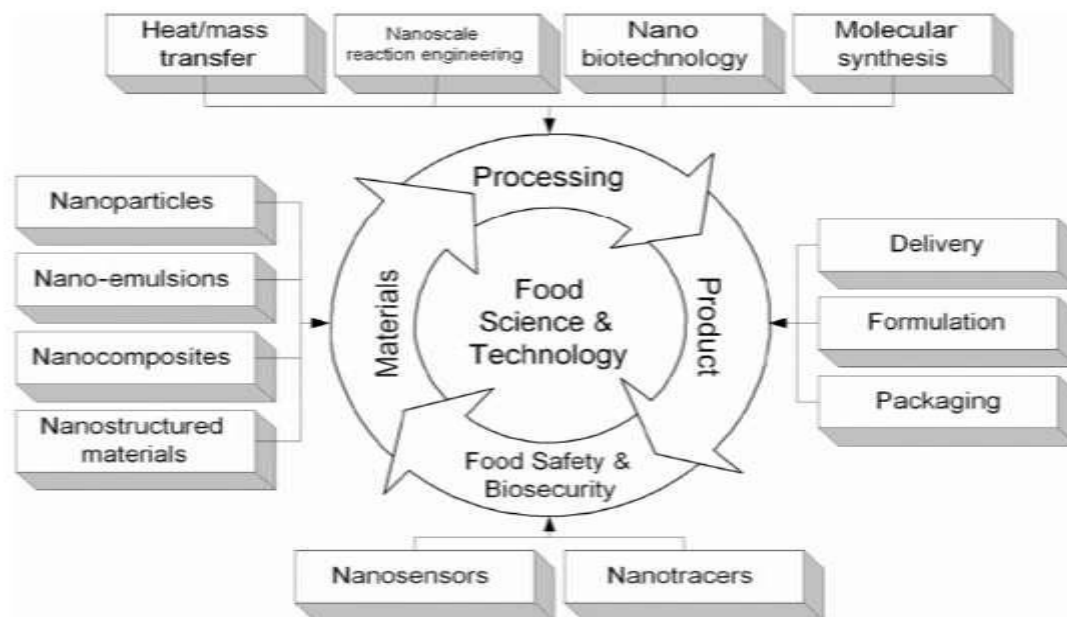


Fig.1: Application matrix of nanotechnology in food science and technology [GuhanNath et al. 2014].

Nanotechnology is contributing to the development of innovative packaging materials that can improve the safety and shelf life of products by providing barrier materials or detect foodborne pathogens. As example, Synthetic amorphous silica (SAS) is used for surface coating of packaging materials, for the clearing of beverages, and mostly as a free-flow and anti-caking agent in many powdered food items (E551) [Aschberger et al. 2015]. Some food materials packaging are equipped with nano sensors is designed to track either the internal or the external conditions of the food products, pellets and containers throughout the supply chain. Such packaging can monitor temperature or humidity over time and then provide relevant information on these conditions [Prasanna&Shanmuganathan 2011]. Also, Nanotechnology is used these days to increase the bioavailability of many vitamins as well as their precursors. The vitamins and precursors which are insoluble in water can be solubilized by a nanoparticle formulation [Prakash et al. 2013]. The unique properties of these nanostructures and nanomaterials including physical, chemical, and biological properties are considerably different from their bulk counterparts alter the understanding of biological and physical occurrence in food systems. Several recent reports and reviews have identified potential applications of nanotechnology for the food sector to improve food safety, to enhance packaging and lead to improved processing and nutrition [Pathakoti et al. 2017].

The next wave of food innovation will require a shift of focus from macroscopic properties to those on the meso- and Nano-scales, as these subsequently control the hierarchical structures in food and food functionality [Paul & Dewangan 2016]. Though the urge of use of nanotechnology in food is increasing day by day the potential (eco) toxicological effects and impacts of nano particles have so far received little attention [Bouwmeester et al. 2009]. Very often the physicochemical characterization of the nano particles is very poor and was reported in less than

15% of the records concerning (eco)toxicity and risk assessment of nano particles. The most tested toxicity endpoints include genotoxicity, acute toxicity, cytotoxicity and repeated dose toxicity [Aschberger et al. 2015]. Before applying nano particles in consumer based products a good understanding of its potential negative impact on biological system is needed.

Nano Particles in Food Processing:

Food processing is the practice to preserve the food by different methods and techniques to transform food to a consumable state and these techniques are designed in such a way that the flavor and quality of the food are kept intact but they are also protected from micro-organisms. The food market demands technologies, which are essential to keep market leadership in the food processing industry to produce fresh authentic, convenient and flavorful food

products and nanotechnology is the answer to it [Chaudhry 2009]. Food processing methods like incorporation nutraceuticals, mineral and vitamin fortification, gelation and viscosifying agents, nutrient delivery and nanoencapsulation of flavors use nanomaterials in their contents [Pradhan et al. 2015]. Nanoparticles are added to many foods to improve flow properties, colour and stability during processing, or to increase shelf life. For example, aluminosilicate materials are commonly used as anticaking agents in granular or powdered processed foods, while anatase titanium dioxide is a common food whitener and brightener additive, used in confectionery, some cheeses and sauces [Alfadul&Elnehwya2010].

Nanoencapsulation:

Nanoencapsulation provide several benefits such as enhance stability, ease of handling, retention of volatile ingredients, protection against oxidation, pH and moisture triggered controlled release, taste making, consecutive delivery of multiple active ingredients, change in flavor character, long lasting organoleptic perception and enhanced bioavailability and efficacy [Marsh & Bugusu 2007]. Nanocapsules are prepared basically in six ways named as nanoprecipitation, emulsion-diffusion, double emulsification, emulsion-coacervation, polymer coating and layer-by-layer [Maynard et al. 2006]. Nanocapsules are used to deliver lipophilic health supplements such as vitamins and minerals in the food, fatty acids and growth hormones, increasing the nutrient content of the food [Dreher 2004]. Patented “Nano drop” delivery systems is in the form of encapsulated materials, such as vitamins. It is administered transmucosally, rather than through conventional delivery systems such as pills, liquids, or capsules [Paul & Dewangan 2016].

That contains a natural biopolymer from yeast cell walls that is intended to bind mycotoxins to protect animals against mycotoxicosis is an example of a food additives. The potential use of an aflatoxin-binding nano-additive for animal feed, which is derived from modified Nano clay, has also been suggested. An NP that adheres to E. coli, comprising a polystyrene base, polyethylene glycol linker and mannose-targeting biomolecule has been developed by scientists. These NPs are designed to be administered through feed to remove food-borne pathogens in the GI tracts of livestock (FAO/WHO, 2010). Nanoparticles of Silica has no nutritional value. In food applications, it is mainly used as a technical additive by encapsulating for food processing. Silicas are especially used as free flowing agents (e.g. tomato powder, table salt and spices). They are

also used as input and dispersion aids in vitamin additives, for example. In powder- type foods, synthetic amorphous silicas prevent clumping and maintain the pouring properties [8].

Some major nano-encapsulation techniques used in food processing are

1. Introduction of novel encapsulation techniques based on cold-set gelation for delivering heatsensitive bioactives including probiotics [GuhanNath et al. 2014].
2. Harnessing the casein micelle, a natural Nano - vehicle of nutrients, for delivering hydrophobic bioactives.
3. Developments and use of Maillard reaction based conjugates of milk proteins and polysaccharides for encapsulating bioactives [Livney 2009].
4. Discovering unique nanotubes based on enzymatic hydrolysis of α -lactalbumin.
5. Introduction of β -lactoglobulin-pectin nanocomplexes for delivery of hydrophobic nutraceuticals in clear acid beverages [GuhanNath et al. 2014].
6. Fatty acid-coated bovine serum albumin nanoparticles for intestinal delivery, and Maillard conjugates of casein and resistant starch for colon targeting [Livney 2009].
7. Development of core-shell nanoparticles made of heat- aggregated -lactoglobulin, nanocoated by beet-pectin, for bioactive delivery [Augustin & Sanguansri 2015].

Nanoemulsions:

Nanoemulsion production for delivery of functional compounds is one of the emerging fields of nanotechnology applied to food industry. Nanoemulsions consist of oil droplets in the nano-ranged size, between 10 and 100 nm dispersed within an aqueous continuous phase, with each oil droplet surrounded by surfactant molecules [Acosta 2009, McClements et. al 2007, 2009]. Nanoemulsions can protect flavor compounds from manufacturing conditions and throughout the beverage's shelf-life. NutraLease, a technology start-up company established by a scientific team, is working to improve the bioavailability of functional compounds. It is claimed that Nanoemulsions can capture the flavor and protect it from temperature, oxidation, enzymatic reactions and hydrolysis and are thermodynamically stable at a wide range of pH values [NutraLease 2011c]. Unilever has made ice cream healthier without compromising on taste through the application of

Nanoemulsions. The objective is to produce ice cream with lower fat content, achieving a fat reduction from the actual 16% to 1% . Nestlé has a patent in water-in-oil emulsions (10–500 nm), aiming at achieving quicker and simpler thawing through the addition of polysorbates and other micelle-forming substances; these are claimed to contribute to a uniform thawing of frozen foods in the microwave [Silva et al. 2012].

Nano Particles in Food Packaging:

Food packaging continues to evolve in response to the advancement of material science and technology, as well as the changing consumers' lifestyle. In today's global economy, packaging not only is essential to enable effective distribution and preservation of food and other consumer products, but also to facilitate their end-use convenience and communication at the consumer levels. With these important functions, packaging has become the third largest industry in the world and it represents about 2% of Gross National Product (GNP) in developed countries (Han, 2005; Robertson, 2005). Packaging provides containment and protects food products during distribution and storage from external and internal unfavorable conditions, such as water vapour, microorganism, gases, odors, dust, and mechanical shock and vibrations. Due to consumers' complex and busy lifestyle in the modern society, food producers are striving to develop functional packaging systems with enhanced end use convenience features. Besides all these functions, it provides essential product information to consumer to facilitate the promotion and advertisement of the product. In advanced packaging systems, these functions are augmented through interactive mechanisms driven by physical, chemical and/or biological processes. Here, intelligent packaging systems are those that possess enhanced function with respect to communication and marketing functions, such as to provide dynamic feedback to the consumer on the actual quality of the product. On the other hand, active packaging is focused on providing protection and preservation of the food through some mechanism activated by intrinsic and/or extrinsic factors (Lim, 2011). Nanotechnology is a powerful interdisciplinary tool for the development of innovative products. It has been predicted that nanotechnology will impact at least \$3 trillion across the global economy by 2020, creating a demand of 6 million employers in various industries (Duncan, 2011). In 2008, the global nanotechnology-related food packaging was US\$4.13 billion, which has been projected to at about 12% compound annual growth rate (" Nano-enabled

Packaging for the Food and Beverage Industry – A Global Technology, Industry and Market Analysis 2009," 2009). With this global trend, it is expected that nanotechnology will provide an important technology push in the food packaging industry to develop advanced packaging applications for fulfilling consumer's needs. Nanotechnology is highly interdisciplinary involving the exploitation of materials with one or more dimensions that are less than 100 nm. Typical nanomaterials can be classified into three main classes: 1) particulates; 2) platelets; and 3) fibers (Schmidt et al., 2002; Thostenson et al., 2005). Due to their nano-sized dimensions, these materials possess very large surface-to-volume ratio and surface activity. When added to compatible polymers, the nanomaterials can dramatically enhance the material properties of the resulting nanocomposites, such as improved mechanical strength, enhanced thermal stability, increased electrical conductivity, and so on (Uskokovic, 2007). Thus, nanomaterials are promising for improving the mechanical and barrier properties of food packages, as well as the development of advanced structures for active and intelligent applications.

A literature review of the safety and regulation of nanotechnologies in food packaging, specifically, the aim of the review was to:

- I. Identify types of nanotechnologies currently used in food contact packaging with an aim to identify those that may result in migration of Nanomaterials from the packaging into food.
- II. Where possible, identify publicly available evidence that the nanotechnologies identified in the previous task are applied in Australia and/or New Zealand, either in domestically produced or imported products.
- III. Ascertain if there is reasonable scientific evidence that the application of nanotechnologies to food packaging materials may potentially pose a risk to public health and safety, due to the migration of Nanomaterials into food and its subsequent ingestion.
- IV. Include a brief synopsis of international regulations currently in place, or in development, which deal with the use of nanotechnologies in food contact packaging.
- V. Use case studies, based on data, to place the above tasks into context and assist to identify data gaps that may hinder formal risk assessment of a novel Nanomaterials intended for food packaging.

Nanoparticles in this report are defined as an engineered form of matter having at least one dimension in the nanometer scale (<100 nm). Similarly, Nanomaterials are materials with any external dimension in the nanoscale or having internal structure or surface structure in the nanoscale.

Numerous applications for Nanomaterials in food packaging have been proposed. Their purpose includes conveying antimicrobial and barrier properties to prevent food spoilage, enhancing film mechanical properties such as emulsification, foaming and water binding capacity, or enhancing other chemical-physical properties of polymers used in food packaging such as thermal stability and crystalline (Aresta et al. 2013, Beltran et al. 2014).

Although many Nanomaterials have been proposed for use in food packaging, this report focuses on those currently used in foods. The focus is also on food packaging per se (e.g. food containers, food wraps and films), rather than food contact materials (e.g. fridges, cutting boards, cutlery). Identifies the functions and types of Nanomaterials proposed for use in food packaging, and identifies those for which there is evidence of their use in world. Nanotechnology-enabled food packaging can generally be divided into three main following categories (Silvestre et al. 2011; Duncan 2011).

Improved packaging:

Whereby Nanomaterials are mixed into the polymer matrix to improve the gas barrier properties, as well as temperature and humidity resistance of the packaging.

Active packaging:

Illustrated by the use of Nanomaterials to interact directly with the food or the environment to allow better protection of the product. For example, silver nanoparticles and silver coatings can provide anti-microbial properties, with other materials being used as oxygen or UV scavengers (Chaudhry et al. 2008, Bott et al. 2014b, Dainelli et al. 2008, FoE 2008, Kuorwel et al. 2015).

Intelligent/smart packaging:

Designed for sensing biochemical or microbial changes in the food (de Azeredo et al. 2013, Emamifar et al. 2010, Fortunati et al. 2013, Llorens et al. 2012, Valipour et al. 2013), for example detecting specific pathogens developing in the food, or specific gases from food spoiling. Some "smart" packaging has also been developed to be used as a tracking device for food safety or to avoid counterfeit.

Nanotechnologies used in food packaging

The information gathered indicated nanotechnology applications in the food sector are increasing worldwide, and many international food companies are exploring their

potential applications. Among the nanotechnology applications for the food sector, nanotechnology-derived food contact materials make up the largest share of the current and short-term predicted market; a range of these are already available in some countries, and it is widely expected they will become increasingly available worldwide in the next few years (Chaudhry et al. 2008). In 2008 the global nano-enabled food and beverage packaging market was 4.13 billion US dollars and was projected to grow to 7.3 billion US dollars by 2014 (Duncan 2011, iRAP 2009).

Current uses

Among several thermoplastics, polyolefin are the most used plastics materials in the food packaging sector. Polypropylene (a type of polyolefin) films are often used because of their transparency, brilliance, low specific weight and chemical inertness. However, polypropylene (PP) (like other polyolefin's and other polymers is also characterized by low barrier properties (i.e. an inherent permeability to gases and other small molecules), which results in poor protection of packaged foods. One of the methods to improve PP and other plastics' barrier deficiencies is to add a second component such as a polymer blend or multilayer, filler, etc (Avella et al. 2007, Duncan 2011, Fabra et al. 2013, Han et al. 2011, Manikantan and Varadharaju 2011, NanosafePACK 2012, Tang et al. 2008). Polymer-based nanocomposites are reported to achieve the same or better barrier properties than their conventional composite counterparts (Avella et al. 2005, 2007; Bott et al. 2014a, Mihindukulasuriya and Lim 2014).

Such nanocomposites are reinforced with small quantities (typically up to 5% by weight) of nanoparticles⁴, which have very high aspect ratios ($L/h > 300$) (Chaudhry et al. 2008, FAO/WHO 2009, NanosafePACK 2012). They are incorporated in addition to the traditional fillers and additives. Nanomaterials have large aspect ratios which, when incorporated as fillers into the walls of packaging, creates an obstacle for gas and moisture passing through packaging walls by increasing the path that the gas/moisture must travel (Hannon et al. 2015).

Apart from conferring barrier properties to extend the shelf life of food (e.g. through an antimicrobial function or an oxygen- or water vapour- permeability barrier), other nanocomposites confer various physical characteristics to make the packaging more tensile, durable, or thermally stable (Beltran et al. 2014, Duncan 2011, NanosafePACK 2012). Examples of other nanocomposites include UV

absorbers (e.g. nano-titanium dioxide, iron oxides, silica, alumina) to prevent UV degradation of plastic polymers, titanium nitride (TiN) used to improve strength of packaging materials, nano-calcium carbonate-polymer composites, nano-chitosan-polymer composites, biodegradable nanoclay composites of starch and polylactic acid⁵, biodegradable cellulose nano-whiskers, and other gas-barrier coatings (e.g. nano-silica) (Reig et al. 2014, Sanchez-Garcia et al. 2010, Siracusa et al. 2008, Smolander and Chaudhry 2010).

A well-known example of one of the first nanocomposites to be explored for use in food packaging to enhance barrier properties is nano-clay, which has been incorporated with nylons, polyolefins, copolymers, epoxy resins, polyurethane, polyethylene terephthalate, etc. Some materials are already commercially available, and used by beverage companies in certain countries. Nano-clay is presented in this report as a case study. Formulation of nanobiocomposites combining nanosilver with nano-clay or other nanomaterials (e.g. titanium dioxide) to enhance both barrier and antimicrobial properties has also been studied for potential future application in food packaging (Busolo et al. 2010, Cozmuta et al. 2014). Other examples of nanomaterials potentially used in food packaging⁶ include alumina (e.g. wheel-shaped alumina platelets used as fillers for plastic materials), nano-precipitated calcium carbonate (to improve mechanical properties, heat resistance and printing quality of polyethylene), polyhedral oligomeric silsesquioxane (POSS) nanoclay (to improve barrier properties), zinc oxide calcium alginate nanofilms (used as a food preservative), and silica/polymer hybrids (to improve oxygen-diffusion barriers for plastics) (Smolander and Chaudhry 2010, Bajpai et al. 2012).

II. CONCLUSION

In conclusion, nanotechnology will serve as an important tool to overcome existing challenges that are associated with packaging materials. This advancement will positively affect the shelf-life, quality, safety, and security of foods, which will ultimately benefit both the producers and consumers. However, precautionary principles should be applied and more research is needed, especially on the migration behaviors of Nanomaterials in food and their potential impacts on health/safety, as well as the environment. A sustainable packaging solution can be achieved only if it is socially responsible, economically viable, and environmentally sound.

REFERENCES

- [1] Acosta, E. (2009). Bioavailability of nanoparticles in nutrient and nutraceutical delivery. *Current Opinion in Colloid & Interface Science*, 14(1), 3–15.
- [2] Alfadul, S.M. & Elneshwy, A.A. (2010), Use of nanotechnology in food processing, packaging and safety – review, *African Journal Of Food Agriculture Nutrition And Development* vol. 10, no.6, 2719-39.
- [3] Aresta, A., Calvano, C., Trapani, A., Cellamare, S., Zambonin, C. and De Giglio, E. (2013). Development and analytical characterization of vitamin(s)-loaded chitosan nanoparticles for potential food packaging applications. *Journal of Nanoparticle Research*. 15: 1-12.
- [4] Aschberger, K., Gottardo, S., Amenta, V., Arena, M., Botelho Moniz F., Bouwmeester H., Brandhoff, P., Mech, A., Quiros Pseudo, L., Rauscher, H., Schoonjans, R., Vittoria Vettori, M., Peters, R. (2015) *Nanomaterials in Food – Current and Future Applications and Regulatory Aspects*, *Journal of Physics: Conference Series* 617, 012032.
- [5] Augustin M.A. & Sanguansri L. (2015) *Micro-and Nano-encapsulation Technologies*, *CSIRO Food & Nutrition*; 1-43.
- [6] Avella, M., Bruno, G., Errico, M. E., Gentile, G., Picciocchi, N., Sorrentino, A. and Volpe, M. G. (2007). Innovative packaging for minimally processed fruits. *Packaging Technology and Science*. 20: 325-335.
- [7] Avella, M., De Vlieger, J. J., Errico, M. E., Fischer, S., Vacca, P. and Volpe, M. G. (2005). Biodegradable starch/clay nanocomposite films for food packaging applications. *Food Chemistry*. 93: 467-474.
- [8] Bajpai, S., Chand, N. and Chaurasia, V. (2012). Nano zinc oxide-loaded calcium alginate films with potential antibacterial properties. *Food and Bioprocess Technology*. 5: 1871-1881.
- [9] Beltrán, A., Valente, A. J. M., Jiménez, A. and Garrigós, M. a. C. (2014). Characterization of poly(ϵ -caprolactone)-based nanocomposites containing hydroxytyrosol for active food packaging. *Journal of Agricultural and Food Chemistry*. 62: 2244-2252
- [10] Bott, J., Störmer, A. and Franz, R. (2014b). A comprehensive study into the migration potential of nano silver particles from food contact polyolefins. In: *Chemistry of Food, Food Supplements, and Food Contact Materials: From Production to Plate*. American Chemical Society. 51-70.
- [11] Bott, J., Störmer, A. and Franz, R. (2014a). A model study into the migration potential of nanoparticles

- from plastics nanocomposites for food contact. *Food Packaging and Shelf Life*. 2: 73-80.
- [12] Bouwmeester, H., Dekkers, S., Noordam, M.Y., Hagens, W.I., Bulder, A.S., Heer, C., Voorde, S.E.C.G., Wijnhoven, S.W.P., Hans J.P. Marvin, H.J.P. & Sips, A.J.A.M. (2009) Review of health safety aspects of nanotechnologies in food production, *Regulatory Toxicology and Pharmacology* 53; 52–62.
- [13] Busolo, M. A., Fernandez, P., Ocio, M. J. and Lagaron, J. M. (2010). Novel silver-based nanoclay as an antimicrobial in polylactic acid food packaging coatings. *Food Additives & Contaminants: Part A*. 27: 1617-1626
- [14] Chaudhry, Q. (2009), *Nanotechnology for Food Applications: Current Status and Consumer Safety Concerns*, AAAS Annual Meeting: Nanofood for Healthier Living? Chicago 16 February 2009.
- [15] Chaudhry, Q., Castle, L., Bradley, E., Blackburn, J., Aitken, R. and Boxall, A. (2008). Assessment of current and projected applications of nanotechnology for food contact materials in relation to consumer safety and regulatory implications. Final report Project A03063. Food Standards Agency. <http://www.food.gov.uk/sites/default/files/a03063.pdf>.
- [16] Chaudhry, Q., Scotter, M., Blackburn, J., Ross, B., Boxall, A., Castle, L., Aitken, R. & Watkins R. (2008), Applications and implications of nanotechnologies for the food sector, *Food Additives and Contaminants*, 25(3): 241–258.
- [17] Cozmuta, M. A., Anca, P., Cozmuta, L. M., Nicula, C., Crisan, L., Baia, L. and Turila, A. (2014). Active packaging system based on Ag/TiO₂ nanocomposite used for extending the shelf life of bread. *Chemical and microbiological investigations. Packaging Technology and Science*. 28: 271-284
- [18] Dainelli, D., Gontard, N., Spyropoulos, D., Zondervan-van den Beuken, E. and Tobback, P. (2008). Active and intelligent food packaging: legal aspects and safety concerns. *Trends in Food Science & Technology*. 19, Supplement 1: S103-S112
- [19] Dreher K.L. (2004) Health and Environmental Impact of Nanotechnology: Toxicological Assessment of Manufactured Nanoparticles, *Toxicological Sciences* 77, 3–5.
- [20] Duncan, T. V. (2011). Applications of nanotechnology in food packaging and food safety: Barrier materials, antimicrobials and sensors. *Journal of colloid and interface science*, 363, 1-24.
- [21] Emamifar, A., Kadivar, M., Shahedi, M. and Soleimanian-Zad, S. (2010). Evaluation of nanocomposite packaging containing Ag and ZnO on shelf life of fresh orange juice. *Innovative Food Science & Emerging Technologies*. 11: 742-748.
- [22] Fabra, M. J., Busolo, M. A., Lopez-Rubio, A. and Lagaron, J. M. (2013). Nanostructured biolayers in food packaging. *Trends in Food Science & Technology*. 31: 79-87.
- [23] FAO/WHO (2009). FAO/WHO expert meeting on the application of nanotechnologies in the food and agriculture sectors: potential food safety implications. Food and Agriculture Organization of the United Page 63 of 75.
- [24] FoE (2008). Out of the laboratory and on to our plates: Nanotechnology in food and agriculture. Friends of the Earth Australia, Europe and USA.
- [25] Fortunati, E., Peltzer, M., Armentano, I., Jiménez, A. and Kenny, J. M. (2013). Combined effects of cellulose nanocrystals and silver nanoparticles on the barrier and migration properties of PLA nanobiocomposites. *Journal of Food Engineering*. 118: 117-124.
- [26] GuhanNath, S., Sam Aaron, I., AllwynSundar Raj, A. & Ranganathan, T.V. (2014) Recent Innovations in Nanotechnology in Food Processing and its Various Applications – A Review, *Int. J. Pharm. Sci. Rev. Res.*, 29(2),; Article No. 22, 116-124.
- [27] Han, D. Y., Tian, Y., Zhang, T., Ren, G. and Yang, Z. (2011). Nano-zinc oxide damages spatial cognition capability via over-enhanced long-term potentiation in hippocampus of Wistar rats. *International Journal of Nanomedicine* 6: 1453-1461.
- [28] Hannon, J. C., Cummins, E., Kerry, J., Cruz-Romero, M. and Morris, M. (2015). Advances and challenges for the use of engineered nanoparticles in food contact materials. *Trends in Food Science & Technology*. 43: 43-62.
- [29] Han, J. H. (2005). *Innovations in food packaging*. Academic Press, (2nd ed). San Diego: CA
- [30] iRAP (2009). Nano-enabled packaging for the food and beverage industry - a global technology industry and market analysis. *Innovative Research and Products Inc. Abstract only*. http://www.innoresearch.net/report_summary.aspx?id=68&pg=107&rcd=FT-102&pd=7/1/2009.
- [31] Kuorwel, K., Cran, M. J., Orbell, J. D., Buddhadasa, S. and Bigger, S. W. (2015). Review of mechanical properties, migration, and potential applications in

- active food packaging systems containing nanoclays and nanosilver. *Comprehensive Reviews in Food Science and Food Safety*. 14: 411-430.
- [32] Lim, L. T. (2011). Active and intelligent packaging materials. *Comprehensive Biotechnology* 2nd Ed., Amsterdam, The Netherlands: Elsevier, 629-644.
- [33] Livney, Y.D. (2009), Milk proteins as vehicles for bioactives, *Curr Opin Colloid Interface Sci*, In Press, Corrected Proof, Available online 20 November 2009, (Accessed February 26, 2010).
- [34] Llorens, A., Lloret, E., Picouet, P. A., Trbojevich, R. and Fernandez, A. (2012). Metallic-based micro and nanocomposites in food contact materials and active food packaging. *Trends in Food Science & Technology*. 24: 19-29.
- [35] Mahmoud, M.B. (2015), Nanotechnology in food industry; advances in food processing, packaging and food safety, *Int.J.Curr.Microbiol.App.Sci*4(5): 345-357.
- [36] Manikantan, M. R. and Varadharaju, N. (2011). Preparation and properties of polypropylene-based nanocomposite films for food packaging. *Packaging Technology and Science*. 24: 191-209
- [37] Marsh K. & Bugusu B. (2007) Food packaging-roles, materials and environmental issues: Scientific status summary, *Journal of food Science*, vol.72, no.3, pp. R39-R55.
- [38] Maynard, A.D., Aitken, R.J., Butz, T., Colvin, V., Donaldson, K., Oberdörster, G., Philbert, M.A., Ryan, J., Seaton, A., Stone, V., Tinkle, S.S., Tran, L., Walker N.J. & Warheit, D.B. (2006) Safe handling of nanotechnology, *Nature* ; 267-269
- [39] McClements, D. J., Decker, E. A., & Weiss, J. (2007). Emulsion-based delivery systems for lipophilic bioactive components. *Journal of Food Science*, 72(8), R109–R124.
- [40] McClements, D. J., Decker, E. A., Park, Y., & Weiss, J. (2009). Structural design principles for delivery of bioactive components in nutraceuticals and functional foods. *Critical Reviews in Food Science and Nutrition*, 49(6), 577–606.
- [41] Mihindukulasuriya, S. and Lim, L.-T. (2014). Nanotechnology development in food packaging: a review. *Trends in Food Science & Technology*. 40: 149-167
- [42] Nano-enabled Packaging for the Food and Beverage Industry – A Global Technology, Industry and Market Analysis 2009. In (2009).
- [43] NanosafePACK (2012). D.1.1 Report on the nanoclays and metal oxide nanoparticles employed on the packaging industry. Project: Development of a best practices guide for the safe handling and use of nanoparticles in packaging industries. Grant Agreement: 286362. Project co-funded by the European Commission. Written by Carlos Fito, ITENE.
http://www.nanosafepack.eu/sites/default/files/news-download-files/NANOSAFEPACK_D1.1_Report%20on%20Nanoclays%20and%20MONPs_r1.pdf. Page 66 of 75.
- [44] NutraLease (2011c). Available at:
<http://www.nutralease.com/Nutra/Templates/showpage.asp?DBID=1&LNGID=1&TMID=84&FID=768>. Accessed 13 April 2011.
- [45] Ozimek, L., Pospiech, E., Narine, S., Nanotechnologies in food and meat processing (2010), *Acta Sci. Pol., Technol. Aliment.* 9(4) 2010, 401-412.
- [46] Paul, S.D. & Dewangan D. (2016) Nanotechnology and Nutraceuticals. *Int J Nanomater Nanotechnol Nanomed* 2(1): 009-012.
- [47] Pathakoti, K., Manubolu, M. & Hwang, H.M. (2017) Nanostructures: Current uses and future applications in food science, *Journal of Food and Drug Analysis* Xxx; 1-9.
- [48] Pradhan, N., Singh, S., Ojha, N., Shrivastava, A., Barla, A., Rai, V., & Bose, S. (2015) Facets of Nanotechnology as Seen in Food Processing, Packaging, and Preservation Industry, *BioMed Research International*; 1-17.
- [49] Prakash, A., Sen S. & Dixit R. (2013) The Emerging Usage and Applications of Nanotechnology in Food Processing Industries: The new age of Nanofood, *Int. J. Pharm. Sci. Rev. Res.*, 22(1), no 21, 107-111.
- [50] Prasanna, P. & Shanmuganathan, S. (2011) Nanotechnology in Food Industry, *Bionano Frontier*, Vol 4(1); 6-11.
- [51] Reig, C. S., Lopez, A. D., Ramos, M. H. and Ballester, V. A. C. (2014). Nanomaterials: a Map for Their Selection in Food Packaging Applications. *Packaging Technology and Science*. 27: 839-866
- [52] Robertson, G. L. (2005). Food packaging: principles and practice. New York: CRC press.
- [53] Sanchez-Garcia, M. D., Lopez-Rubio, A. and Lagaron, J. M. (2010). Natural micro and nanobiocomposites with enhanced barrier properties and novel functionalities for food biopackaging applications. *Trends in Food Science & Technology*. 21: 528-536.

- [54] Schmidt, D., Shah, D., & Giannelis, E. P. (2002). New advances in polymer/layered silicate nanocomposites. *Current Opinion in Solid State and Materials Science*, 6, 205-212.
- [55] Silvestre, C., Duraccio, D., and Sossio, C. 2011, "Food packaging based on polymer nanomaterials", *Progress in Polymer Science*, vol. 36, pp. 1766–1782
- [56] Silva, H.D., Cerqueira M.A. & Vicente, A.A. (2012) Nanoemulsions for Food Applications: Development and Characterization, *Food Bioprocess Technol* 5:854–867.
- [57] Siracusa, V., Rocculi, P., Romani, S. and Rosa, M. D. (2008). Biodegradable polymers for food packaging: a review. *Trends in Food Science & Technology*. 19: 634-643.
- [58] Tang, X., Alavi, S. and Herald, T. J. (2008). Barrier and mechanical properties of starch-clay nanocomposite film. *Cereal Chemistry*. 85: 433-439.
- [59] Thostenson, E. T., Li, C., & Chou, T.-W. (2005). Nanocomposites in context. *Composites Science and Technology*, 65, 491-516.
- [60] Uskokovic, V. (2007). Nanotechnologies: What we do not know. *Technology in society*, 29, 43-61.